Evaluating Hydrological Uncertainties Arising due to DEM Resolution: Study for the Himalayan River Basin Gandak

Brijesh Kumar[1*], Kanhu Charan Patra[1], Venkat Lakshmi[2]
[1]Department of Civil Engineering, National Institute of Technology Rourkela, India;
[2]Department of Earth and Ocean Sciences, University of South Carolina, USA
[*]E-mail: brijeshag1684@gmail.com

Abstract- Digital Elevation Model (DEM) is a most significant spatial input for the physical, hydrological models. Sometimes, the DEM resolution is needed to be changed to manage quick simulation in the large basins and to provide a pre-defined grid size required for a physical model. In such conditions, resampling of DEM data to specific grid size is shouted. In this study, the effect of DEM resolutions resampled with three methods (1) Nearest Neighborhood (2) Bilinear and (3) Cubic Convolution have been examined in the Gandak River Basin (GRB). The result for the GRB shows that stream flow is significantly affected by DEM resolution, where it overestimates the flow for coarser resolutions (DEM grid size >150m). T-test statistics demonstrates that the flow is significant at yearly time step for the coarser resolution (DEM grid size >500m) while it is insignificant at monthly time step.

Keywords Hydrological Uncertainty, Resampling methods, DEM grid size, Gandak basin, Himalaya, SWAT

1. Introduction

The Hindu-Kush Himalayan region- known as "roof of the world" is significantly affected by anthropogenesis and climate change issue. This is threatening the human health, food production and natural ecosystem in the region [1]–[5]. Due to difficulty in the simulation of hydrology for Himalayas, it has become a prime field of research in this region. Use of physically based models (such as SWAT model) has proven their usefulness to estimate hydrological parameters from watersheds and effectively are being used in environmental risk management worldwide since last two decades [6]–[10].

Uncertainty in the simulated hydrological results should be understood to better quantify the parameters. A considerable progress has been made in the quantification of model uncertainty [11], [12] due to process parameters . The ability of physically based models to predict the hydrological process significantly depends on the input forcing .Therefore, it should be in more attentions [13].

Digital Elevation Models (DEMs) are key spatial input to derive watershed boundary, slope gradient, channel network, flow direction, flow accumulation and many other for hydrological model like Soil and Water Assessment Tool (SWAT) and Topography-based hydrological model (TOPMODEL) [9], [14], [15]. For example, low-resolution DEM may result in decrease slope which directly impact the stream network, sub-basin delineation and finally affects the number of Hydrological Response Units (HRUs) [16].

Several studies have demonstrated the effect of DEM resolution, sources and resampling methods on the output of hydrological models. [17] Investigated the impact of DEM mesh size (from 20-200 m) to simulate the flow, sediment and NO_3-N load at the outlet of 21.8 km^2 large agricultural watershed. He found that decrease in mesh size beyond a threshold limit may not substantially affect the computed runoff flux but significantly affects the sediment and NO_3-N load. [18] Evaluated the sensitivity of SWAT model to simulate flow due to original and resampled DEM in the Charlie Creek basin, Florida, USA. They concluded that the accuracy of simulated streamflow significantly differs between original 90m, 30 m and resampled 90 m DEMs. [7] Evaluated the performance of two DEM sources ASTER GDEM V 1.0, SRTM V 4.1 with eleven resampled DEMs ranging between 5m -140m. They chose Xiekengxi River watershed (81.7 Km^2) for the case study and concluded resampling DEMs to course resolution has a decreasing trend to predict total nitrogen (TN), total phosphorous (TP), and sediment; predicted runoff is not sensitive resampling resolution.

Previous studies were focused on the hydrological uncertainties in the relatively small and low relief basins. Very little attention has been made for large mountainous and glacier river basins like Himalayan River basins Gandak [19] and also with high-resolution temporal outputs [9]. So, it is meaningfull to carry out the DEMs based hydrological in this region.

2.MATERIALS AND METHODS

2.1 Description of Study area

The Gandak River Basin (GBR) - a trans-boundary river basin whose area lies in the China (Tibet), Nepal and India. River originates at the high altitudes (7620m from m.s.l.) in the northeast of Dhaulagiri, nearby Tibet -Nepal border at geographical position 29.3ºN and 83.97ºE; whereas it confluences with river Ganga river near Patna, Bihar (India). The GBR covers a very large geographical area (44797 Km^2) between 25.6º and 29.4 º N and 82.8 º and 85.82 º E out of which 7620 Km^2 falls in India and rest in Nepal and Tibet. Basin has a very young and fragile geology, causing muddy flood in the India portion due to intense rainfall (maximum 24-hour rainfall of 50 years is 2800mm) occurring in the mid hills of Nepal. The location of the study area is given in Figure 1.

The basin comprises of diverse ecosystems and biodiversity, from the alpine arid rain shadow areas of the Tibetan Plateau through the steep topography of the high mountains, including some of the world's highest point, Shivalik hills, Dhaulagiri (~8100 MSL), to the flat plains (33 MSL) towards its confluence. Gandak River runs 380 Km in Nepal and Tibet and 260 Km in India before reaching to Patna. The river has six sub-catchments namely Kali Gandak, Seti, Marshandi, Budhi Gadak, Trisuli and Rapti, out which five arises in the highly elevated areas of Himalaya. In the very north of the Himalayan Range, the basin is categorized by a dry alpine climate with very low precipitation; however towards southern part which outspreads from mid-hills to very flat area (Indian portion), has a humid climate with relatively high precipitation. Based on GlobeLand30 [20] global land cover data 2010, GBR has 33.1% forest, 22.04 agricultural land, 20.78% grassland, 10.24% ice/snow cover, 9.4 % barren land, and only 0.16 % urban land.

2.2 Description of the data used

In this study, we used DEM (SRTM 90m v4.1), FAO soil map, land use map (GlobeLand30-) one time spatial forcing and hydro-climatic data. GlobeLand30- land use data for year 2010 was collected from China's global land cover mapping site (http://glc30.tianditu.com/). Also, we used temporal forcing for precipitation-APHRODITE and Climate Forecast System Reanalysis (CFSR) for meteorological parameters like minimum and maximum temperature, relative humidity, wind speed and sunshine hours. Thirteen years (2000-2012) of observed discharge data at Triveni site was obtained from Central Water Commission (CWC) government of India to calibrate the SWAT model.

The SRTM 90 m [21] is a joint project between the United States National Aeronautics and Space Administration (NASA), the German and Italian space agency and the National Imagery and Mapping Agency (NIMA). Mission started its data acquisition in February 2000 and covers almost 80% of the globe between 60N to 56S. To study the impact of DEM resolution and resampling methods on hydrology, forty-eight scenarios [sixteen DEMs (40m, 50m, 60m, 70m, 80m, 90m, 100m, 150m, 200m, 300m, 400m, 500m, 600m, 700m, 800m, 1000m of grid size) for each resample method viz. nearest neighbor (N), bilinear (B) and cubic convolution (C)] were calculated from original SRTM 90m v4.1 using ArcGIS desktop10.2 (ESRIInc., Redlands, CA).

2.3 Evaluation of uncertainty in the flow due to DEM grid size for SWAT model

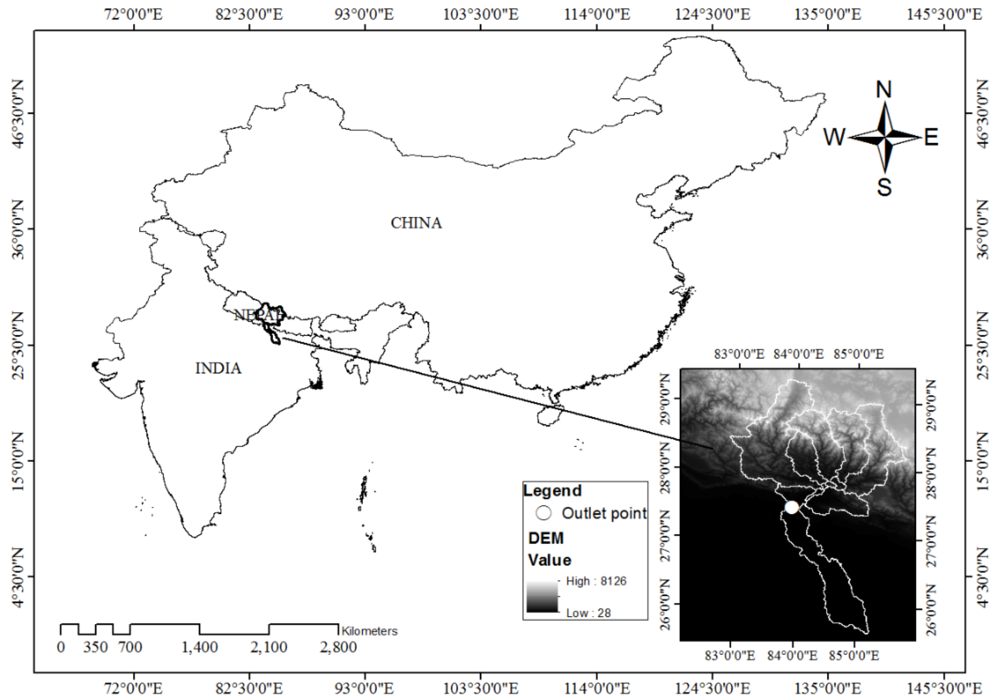

Fig. 1.1 Location map of the study area

SWAT model [22] is a semi-distributed hydrological model which is originally developed by the United States Department of Agriculture-Agricultural Research Service (USDA-ARS). It calculates the runoff based on the Curve Number (CN) method developed by [23] (USDA-SCS 1972. We used SWAT2012 (http://swat.tamu.edu/) in this study. It divides the watershed into sub-basins which are then further divided into HRUs based on the unique land use and soil group. Sub-basins preserves the flow paths, channels, slope and boundaries that are required for routing of flow, sediments and nutrients load and these rely on DEM. DEM majorly influences the flow and nutrients load modeling through topographic attributes [6]. Thus, during evaluation of SWAT model outputs uncertainty due to DEM resolution and resampling methods, it is required to inspect the uncertainties of watershed topographic inputs. Therefore, we examined the following topographic characteristics from basin: number of HRUs and sub-basins, area, mean basin slope, mean basin altitude, and perimeter; from sub-basin: field slope and longest path; from reach: mean slope, mean reach depth and width (Appendix I). Because of there were more than one sub-basins and reach in this study, all the considered topographic characteristics were averaged to simplify the assessment.

Initially, we calibrated the SWAT model for flow at the outlet on a daily basis. The calibration period was eight years (2000-2208) and we considered both land and snow parameters to achieve good statistics between observed and simulated flow. SUFI-2 optimization algorithm was used to optimize the flow with Nash–Sutcliffe efficiency (NSE) as the objective function. The model performance was considered satisfactory if NSE ≥ 0.5, $R^2 \geq 0.5$ and PBIAS $= \pm$ 25%. Thereafter, the calibrated parameters were transferred to other forty eight scenarios to calculate the uncertainty. All forty eight scenarios were run from 1983-2007 (nearly 25 years) on daily basis. Relative difference (RD) statistical parameter has been employed to ascertain the uncertainty (equation 1.1)

$$RD = \frac{P_{x\_R} - P_{90B}}{P_{90B}} \qquad \text{equation 1.1}$$

Where P_{i_R} monthly predicted SWAT outputs at DEMs resolution (x) and resampling techniques (R) and P_{90B} is the monthly SWAT outputs at 90 m bilinear resampled DEM. Monthly SWAT outputs of P_{90B} was considered the corresponding base value and it was assumed to be the best. The results and discussion section of this manuscript use RD as an uncertainty measure (RD of +ve i.e. overestimation and RD of –ve i.e. underestimating).

ISBN: 978-81-931974-0-0 © T R Publication

3. RESULTS AND DISCUSSION

3.1 Uncertainty in the modelled flow

For flow (Fig. 1.2), RD was ±10% and most of the time ~0 for scenarios falling within ≤300 m resolution; however 60N and 90N were two aspersions where RD was found >10%. RD was +ve for DEMs >300 to <700 m resolution and beyond 700 m resolution it –ve for B and C. The maximum RD of flow was 34.7% for 600B. For most of the time RD of flow is overestimating in nature for scenarios <150m of DEM resolution. When we compared the RD between N, B and C, it was found that it B shows less variation of RD from zero below 300m resolution. It also explored the variation of RD within a season. For summer/monsoon period (April to Juley), RD is almost bell shape and peak increases with coarser resolution. In this period also, scenarios falling ≤300 m of the resolution were having relatively mild peak than coarser resolution.

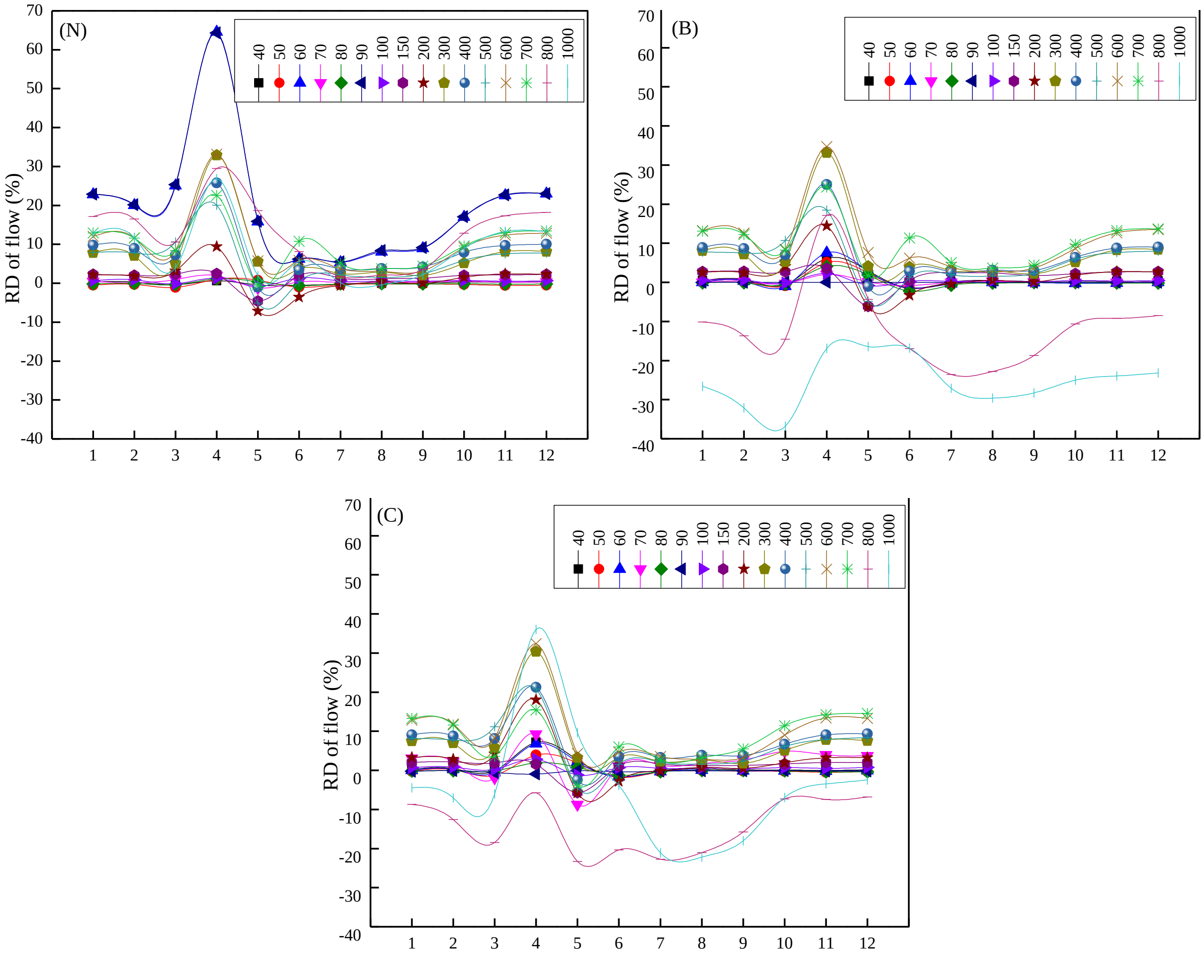

Fig. 1.2 The temporal sensitivity of average monthly SWAT flow output (period 1983-2007) at the different months varying with different DEM resolution and resampling techniques.

SWAT model does not adjust CN for slope [7]. That is why in this study mean basin slope (Appendix I) changes with coarser resolution (for all resampled methods), but runoff is not sensitive till 600m. We had observed a stable trend of runoff and perimeter variation for different resampled resolution. Secondly, we had seen the comparable variation of flow and mean altitude for resampled resolution >600m. This is only due to change of temperature lapse rate and precipitation lapse rate in the snow module of SWAT model. Temperature and precipitation lapse rate are the function of elevation. The change elevation due to resampling to courser resolution also changes the mean elevation of elevation bands. This ultimately affects the snowpack and snowmelt and finally resultant flow. We have seen significant change in elevation for resolutions >700m for B and C, it explains the significant change in flow for counterpart scenarios. The overestimation nature of (+ve RD) for DEMs >300 to <700 m resolution is mainly attributed to the changes in water accumulation areas [7].

It is very important to see the significance of the change in trend between base outputs (*90B*) and others mainly with change in spatial resolution, temporal resolution and resample methods. We used *T-test* statistics to see the significance in trend (if any exists). The flow (Table 1.1), has no significant trend at yearly scale due to resolution till 500m resolution for each N, B, and C except at 60N and 90N where it was found significant. On the other hand, at monthly scale, there was no any significant change in trend caused by DEM resolution for all resampling methods. This simplifies that the effect of DEM resolution is not significantly attributes the error on the monthly scale, whereas its accumulated result is significant for courser temporal resolution i.e. yearly time interval and for courser DEM resolution (>500m).

Table 1.1: shows t-test statistics of yearly and monthly flow (1983-2007) for three different resampling methods.

DEMs	**Nearest Neighbor**				**Bilinear**				**Cubic Convolution**			
	Yearly		Monthly		Yearly		Monthly		Yearly		Monthly	
	t-Stat	Signi	t-Stat	Signi.	t-Stat	Signi.	t-Stat	Signi.	t-Stat	Signi.	t-Stat	Signi.
40	0.01	No	0.00	No	0.08	No	0.01	No	0.04	No	0.00	No
50	0.08	No	-0.01	No	0.02	No	0.00	No	-0.06	No	-0.01	No
60	3.23	Yes	0.33	No	-0.01	No	0.00	No	-0.01	No	0.00	No
70	0.06	No	0.01	No	0.01	No	0.00	No	0.51	No	0.05	No
80	-0.05	No	0.00	No	-0.08	No	-0.01	No	-0.06	No	-0.01	No
90	3.27	Yes	0.33	No	0.00	No	0.00	No	-0.05	No	-0.01	No
100	0.16	No	0.02	No	0.08	No	0.01	No	0.15	No	0.02	No
150	0.35	No	0.04	No	0.48	No	0.05	No	0.32	No	0.03	No
200	-0.01	No	0.00	No	0.08	No	0.01	No	0.19	No	0.02	No
300	1.17	No	0.12	No	1.22	No	0.12	No	1.07	No	0.11	No
400	1.42	No	0.14	No	1.17	No	0.12	No	1.29	No	0.13	No
500	0.84	No	0.09	No	0.84	No	0.09	No	0.90	No	0.09	No
600	1.59	No	0.17	No	1.67	Yes	0.18	No	1.55	No	0.16	No
700	1.79	Yes	0.19	No	1.84	Yes	0.20	No	1.68	Yes	0.16	No
800	1.98	Yes	0.21	No	-4.94	Yes	-0.54	No	-5.11	Yes	-0.53	No
1000	1.90	Yes	0.12	No	-7.45	Yes	-0.83	No	-3.46	Yes	-0.40	No

4. CONCLUSINS

DEM is the key spatial input forcing for physically based hydrological models which is causing uncertainty in hydrological outputs. Some times in hydrological modeling we need to coarser size of grid to faster the simulation and sometimes, we need specific grid size for model input. In such cases we need to resample the grid size. In this study we studied the SWAT model uncertainties due to DEM resolution and resampling methods to simulated flow. The result reveals that the topographical parameters alter with change in DEM resolution. This is the key causing uncertainty in the hydrological outputs. The RD results show that the flow variation is $\pm 10\%$ for DEM resolution <300m.On the other hand, the *t-test* statistics shows no significant trend at monthly time step however; it is significant at monthly time step for DEM resolution >500m. Among Nearest neighborhood, Bilinear and Cubic Convolution resampling methods, bilinear method shows less RD than others. Therefore, Bilinear resampling method with <300m of DEM resolution can be used for flow modelling in this region.

ACKNOWLEDGEMENTS

Authors would like to pay a sincere thanks to anonymous reviews and editors for their possible critical comments and suggestions.

REFERENCES

[1] Rao, R.J., 2001. Biological resources of the Ganga River, India. Hydrobiologia 458, 159–168. doi:10.1023/A:1013173204091

[2] Sati, S.C., Paliwal, P.C., 2008. Physico-chemical and bacteriological analysis of Kosi River water in central Himalaya. Pollut. Res. 27, 179–183.

[3] Misra, A.K., 2010. A River about to Die: Yamuna. J. Water Resour. Prot. 02, 489–500. doi:10.4236/jwarp.2010.25056

[4] Khawas, V., 2007. Environmental Challenges and Human Security in the Himalaya, in: "Himalayas in the New Millennium: Environment, Society, Economy and Polity"January 11-12, 2007. University, Centre for Himalayan Studies North Bengal, Darjeeling.

[5] Sharma, Y., 1997. Case Study I * - The Ganga , India. Water Pollut. Control - A Guid. to Use Water Qual. Manag. Princ.

[6] Chaubey, I., Cotter, A.S., Costello, T.A., Soerens, T.S., 2005. Effect of DEM data resolution on SWAT output uncertainty. Hydrol. Process. 19, 621–628. doi:10.1002/hyp.5607

[7] Lin, S., Jing, C., Coles, N.A., Chaplot, V., Moore, N.J., Wu, J., 2013. Evaluating DEM source and resolution uncertainties in the Soil and Water Assessment Tool. Stoch. Environ. Res. Risk Assess. 27, 209–221. doi:10.1007/s00477-012-0577-x

[8] Shen, Z.Y., Chen, L., Liao, Q., Liu, R.M., Huang, Q., 2013. A comprehensive study of the effect of GIS data on hydrology and non-point source pollution modeling. Agric. Water Manag. 118, 93–102. doi:10.1016/j.agwat.2012.12.005

[9] Zhang, P., Liu, R., Bao, Y., Wang, J., Yu, W., Shen, Z., 2014. Uncertainty of SWAT model at different DEM resolutions in a large mountainous watershed. Water Res. 53, 132–144. doi:10.1016/j.watres.2014.01.018

[10] Tan, M.L., Ficklin, D.L., Dixon, B., Ibrahim, A.L., Yusop, Z., Chaplot, V., 2015. Impacts of DEM resolution, source, and resampling technique on SWAT-simulated streamflow. Appl. Geogr. 63, 357–368. doi:10.1016/j.apgeog.2015.07.014

[11] Wagener, T., Gupta, H. V., 2005. Model identification for hydrological forecasting under uncertainty. Stoch. Environ. Res. Risk Assess. 19, 378–387. doi:10.1007/s00477-005-0006-5

[12] Skeffington, R.A., Whitehead, P.G., Abbott, J., 2006. Quantifying uncertainty in critical loads: (B) acidity mass balance critical loads on a sensitive site. Water. Air. Soil Pollut. 169, 25–46. doi:10.1007/s11270-006-2218-9

[13] Bormann, H., 2008. Sensitivity of a soil-vegetation-atmosphere-transfer scheme to input data resolution and data classification. J. Hydrol. 351, 154–169. doi:10.1016/j.jhydrol.2007.12.011

[14] Wang, H., Wu, Z., Hu, C., 2015. A Comprehensive Study of the Effect of Input Data on Hydrology and non-point Source Pollution Modeling. Water Resour. Manag. 29, 1505–1521. doi:10.1007/s11269-014-0890-x

[15] Yang, D., Herath, S., Musiake, K., 2001. Spatial resolution sensitivity of catchment geomorphologic properties and the effect on hydrological simulation. Hydrol. Process. 15, 2085–2099. doi:10.1002/hyp.280

[16] Sharma, A., Tiwari, K.N., 2014. A comparative appraisal of hydrological behavior of SRTM DEM at catchment level. J. Hydrol. 519, 1394–1404. doi:10.1016/j.jhydrol.2014.08.062

[17] Chaplot, V., 2005. Impact of DEM mesh size and soil map scale on SWAT runoff, sediment, and NO3-N loads predictions. J. Hydrol. 312, 207–222. doi:10.1016/j.jhydrol.2005.02.017

[18] Dixon, B., Earls, J., 2009. Resample or not?! Effects of resolution of DEMs in watershed modeling. Hydrol.

Process. 23, 1714–1724. doi:10.1002/hyp.7306

[19] Nepal, S., Shrestha, A.B., 2015. Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basins: a review of the literature. Int. J. Water Resour. Dev. 0627, 1–18. doi:10.1080/07900627.2015.1030494

[20] J Chen, J.J., Liao, A., Cao, X., Chen, L., Chen, X., He, C., Han, G., Peng, S., Lu, M., Zhang, W., Tong, X., Mills, J., 2015. Global land cover mapping at 30 m resolution: A POK-based operational approach. ISPRS J. Photogramm. Remote Sens. 103, 7–27. doi:http://dx.doi.org/10.1016/j.isprsjprs.2014.09.002

[21] Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2008. Hole-filled SRTM for the globe version 4. Available from CGIAR-CSI SRTM 90 m database srtm.csi.cgiar.org.

[22] Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: model development. J. Am. Water Resour. Assoc. 34, 73–89. doi:10.1111/j.1752-1688.1998.tb05961.x

[23] Soil Conservation Service Engineering Division, 1972. Section 4: Hydrology, in: National Engineering Handbook. pp. 10–1 – 10–22.

Appendix I: Topographical characteristics of the study area for different resampling methods and DEM Resolutions

DEMs (m)			40	50	60	70	80	90	100	150	200	300	400	500	600	700	800	1000
ALTITUDE (m)	MIN	N	113	113	113	113	113	113	113	113	113	115	115	114	115	117	115	118
		B	114	114	115	115	115	115	115	115	114	115	115	114	118	117	115	118
		C	112	112	112	112	113	111	112	113	112	114	114	114	114	115	112	115
	MAX	N	8143	8143	8143	8143	8143	8143	8139	8115	8143	8105	8103	8103	8033	8010	8060	7860
		B	8141	8136	8135	8130	8131	8126	8134	8116	8125	8111	8109	8086	8044	7989	8025	7865
		C	8147	8145	8145	8137	8145	8138	8145	8122	8134	8113	8111	8087	8043	7996	8035	7878
	MEAN	N	2702.2	2702.1	2701.8	2701.8	2701.9	2702.1	2702.3	2702	2702.2	2703.3	2703.7	2702.2	2704.8	2707	2710	2708.5
		B	2701.9	2701.9	2702	2701.9	2701.9	2701.9	2701.8	2702	2702.1	2703.1	2703.9	2702.4	2703	2707.6	2712.4	2741.8
		C	2701	2702	2702	2702	2702	2702	2702	2702	2702	2703	2704	2702	2703	2708	2713	3371
	SD	N	1899.7	1899.6	1899.7	1899.7	1899.8	1899.8	1899.7	1899.7	1899.7	1900	1900.3	1899.1	1900.8	1901.6	1903	1902.5
		B	1899.6	1899.6	1899.6	1899.5	1899.6	1899.6	1899.5	1899.6	1899.6	1899.8	1900.2	1899.1	1899.6	1901.5	1889.3	1908.9
		C	1899.6	1899.7	1899.6	1899.6	1899.7	1899.6	1899.5	1899.7	1899.7	1900	1900.3	1899.2	1899.7	1901.6	1898.5	1922.9
SLOPE (%)	MIN	N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	MAX	N	915	687	572	478	419	365	432	313	253	223	187	164	152	142	127	117
		B	729	600	466	378	367	344	332	295	266	218	186	163	151	140	130	118
		C	827	702	568	439	389	364	342	302	270	218	187	164	152	140	131	118
	MEAN	N	53	51	50	50	49	48	47	44	42	38	35	32	30	28	25	23
		B	49	49	49	48	48	47	46	44	42	38	34	32	30	28	26	23
		C	51	50	50	49	48	48	47	44	42	38	35	32	30	28	26	19
	SD	N	37	35	36	34	32	30	31	28	27	24	23	21	20	19	17	16
		B	31	31	30	30	30	29	29	27	26	24	23	21	20	19	18	16
		C	33	32	31	31	30	30	29	28	26	24	23	21	20	19	18	16
		B	1580	1575	1575	1563	1562	1554	1556	1523	1498	1468	1454	1411	1378	1386	1363	1398
		C	1598.6	1587.6	1584.6	1574.7	1566.6	1559.9	1559	1527.6	1502	1470.6	1462.4	1410	1380	1386	1361.6	1532
	AREA (Ha)	N	3636949	3636831	3637338	3637435	3637484	3636897	3638079	3637816	3638260	3639501	3640208	3637550	3642192	3648638	3651480	3654200
		B	3637564	3637619	3637617	3637605	3637625	3637370	3637486	3638027	3637952	3639492	3640768	3637575	3640284	3646874	3667776	370850
		C	3637025	3637286	3637322	3637333	3637375	3637127	3637189	3637989	3637928	3639618	3640752	3637425	3639924	3646776	3667840	5137500
	REACH	N	11	11	11	11	11	11	11	11	11	11	11	11	11	9	11	11
		B	11	11	11	11	11	11	11	11	11	11	11	9	11	9	13	11
		C	11	11	11	11	11	11	11	11	11	11	11	9	11	9	13	11
	HRU	N	107	116	122	124	121	116	121	124	129	133	139	155	162	149	188	159
		B	120	121	121	118	120	121	125	128	135	138	147	134	160	143	195	186
		C	121	122	122	119	120	119	120	128	131	140	146	135	162	143	195	159